International Journal of All Research Education and Scientific Methods (IJARESM),
ISSN: 2455-6211, Volume 13, Issue 5, May-2025, Available online at: www.ijaresm.com

Optimized Design and Performance Analysis of Smart Prepaid Energy Meter System for Enhanced Efficiency

Miss. D. A. Suryawanshi[1], Pratik Anil Bhoite[2], Vinit Milind Kurane[3], Onkar Vilas Patil[4], Rushikesh Rajendra Salunkhe[5]

[1,2,3,4,5]Department of Electrical Engineering, ADCET Ashta, India

----------**********----------

ABSTRACT

Traditional postpaid energy metering systems often suffer from inefficiencies such as delayed billing, unauthorized electricity usage, and a lack of real-time consumption monitoring. To address these challenges, this paper presents a Smart Prepaid Energy Meter System that leverages QR code-based recharging to enable seamless electricity unit top-ups. Unlike conventional billing methods, this system ensures prepaid transactions, preventing outstanding dues and reducing the risk of disconnections. Additionally, it provides real-time energy consumption monitoring, allowing consumers to track and optimize their electricity usage. The proposed system is built using IoT and microcontroller-based technologies, ensuring automated, secure, and transparent energy management. By eliminating manual meter readings and enhancing user control, this system promotes efficient energy utilization and helps both consumers and utility providers manage electricity distribution more effectively. Experimental validation demonstrates the system's feasibility in reducing energy wastage, improving billing accuracy, and enhancing user convenience. This innovation is a step towards smart grid integration, paving the way for digitalized and consumer-centric power management solutions.

Keywords—Prepaid Energy Meter, QR Code, IoT, Real Time Monitoring.

INTRODUCTION

Electricity consumption is a crucial aspect of modern life, and efficient metering systems play a vital role in ensuring accurate billing and resource management. Traditional postpaid energy meters often suffer from drawbacks such as delayed billing cycles, unauthorized power usage, and lack of real-time monitoring, leading to financial losses for both consumers and utility providers. The increasing demand for automated, transparent, and consumer-friendly energy management has driven the need for advanced solutions in the field of metering technology.

To address these challenges, this paper presents a Smart Prepaid Energy Meter System that integrates a QR code-based recharge mechanism with real-time consumption monitoring. This system enables users to conveniently purchase and recharge electricity units through a digital platform, eliminating the need for conventional bill payments. Unlike postpaid meters, where users are billed after consumption, this prepaid approach ensures that energy usage is restricted to the available balance, thereby preventing outstanding dues and power disconnections due to non-payment.

The proposed system is designed using IoT and microcontroller-based technology to enable automated billing, seamless recharge, and continuous monitoring of energy usage. Consumers can track their electricity consumption in real time, allowing them to make informed decisions on power usage and reduce unnecessary wastage. Additionally, the implementation of a smart prepaid metering system contributes to better load management, reduced operational costs for utility providers, and enhanced security against power theft.

This paper explores the design, implementation, and performance evaluation of the proposed smart energy meter system. It highlights the advantages of digital prepaid energy management and demonstrates how the integration of QR-based transactions and IoT technology can lead to a more efficient and consumer-centric electricity distribution system.

LITERATURE REVIEW

The author discusses the challenges utilities face in bill collection and energy theft in developing countries, highlighting the limitations of existing prepaid metering systems. The paper proposes a smart prepaid metering framework with QR-based recharge, IoT integration, and real-time monitoring to enhance efficiency, accessibility, and security in electricity management[1]. The authors discuss the role of smart metering in Smart Grids, emphasizing its impact on energy production, distribution, and consumption. They highlight the advantages of smart meters over conventional meters, including two-way communication, real-time monitoring, energy quality measurement, and remote control capabilities

such as tariff changes and power disconnection. The paper also addresses the importance of fast data transfer between meters and control centers, noting that Power Line Communication (PLC) and wireless technologies are commonly used due to the high cost of fiber or copper networks[2].

A smart card-based prepaid electricity system that allows users to recharge electricity units in advance, ensuring secure transactions and efficient energy management. The system integrates microcontrollers and smart cards for authentication, reducing the risk of unauthorized usage and electricity theft. Additionally, it facilitates real-time monitoring of energy consumption, helping both consumers and utilities manage power distribution effectively. The study highlights the importance of secure prepaid solutions in modern electricity metering and contributes to the development of cost-effective and efficient billing mechanisms[3].

METHODOLOGY

The hardware comprises an ESP32 microcontroller, a current transformer (CT sensor) for current measurement, a voltage divider for voltage sensing, and a relay module for load control. A TFT display (ILI9341) provides users with real-time data on energy consumption and balance. Internet connectivity enables cloud-based data storage and remote monitoring. The system continuously records voltage and current values, which are used to calculate power consumption using $P = V \times I$. The total energy usage is determined as $E = P \times t$, helping users monitor their electricity usage effectively.

One of the core features of this system is its QR code-based prepaid recharge. Users can purchase electricity units online, generating a unique QR code containing transaction details and the number of units bought. This QR code is scanned via the meter's interface, allowing the microcontroller to decode the information and update the balance accordingly. The updated balance is displayed on the TFT screen, and a cloud database stores the transaction details for future reference.

To ensure prepaid functionality, an automatic power cutoff mechanism is integrated. The relay module, controlled by the microcontroller, maintains the power connection if the balance is available. When the balance reaches zero, the relay disconnects the power supply, preventing further usage until a recharge is performed. The system alerts users through both onscreen notifications and cloud-based alerts, ensuring timely recharges to avoid power disconnection.

For enhanced usability, the system supports real-time energy monitoring through cloud integration. The ESP32 microcontroller transmits energy consumption data to a cloud server using Wi-Fi connectivity. Users can access this data via a mobile application or web interface, allowing them to track their electricity usage remotely. The system also stores historical consumption data, which can be analyzed to optimize energy usage. Additionally, utility providers can leverage this data for load forecasting and distribution planning, improving overall grid efficiency.

The software is developed using Arduino IDE and Embedded C, ensuring efficient execution of functions like data acquisition, balance updates, and relay control. Communication between the microcontroller and the cloud is established using MQTT or HTTP protocols, ensuring secure and reliable data transfer. The TFT display provides an intuitive user interface, displaying real-time power usage, available balance, and recharge status.

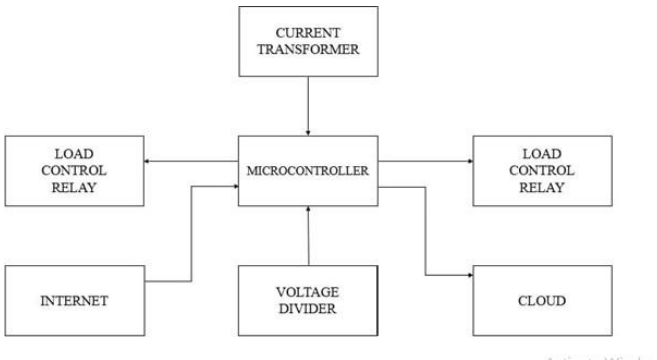

Fig: 1 Block Diagram Of Energy Meter System

To validate system performance, rigorous testing is conducted across different scenarios. Accuracy testing ensures that energy readings match conventional meters, while QR code transaction testing verifies seamless recharge functionality. The relay control mechanism is tested to confirm power disconnection upon balance depletion. Additionally, IoT connectivity tests ensure that real-time updates are accurately reflected on cloud platforms and user interfaces.

Table 1.Comparative Analysis Of Two Systems

Feature	Conventional Energy Meters	Prepaid Smart Energy Meters
Billing System	Postpaid – based on monthly consumption	Prepaid – pay before usage
Meter Reading	Manual meter reading by personnel	Automatic remote reading via communication networks
Accuracy	Subject to manual reading errors	High accuracy with real-time data collection
User Control	Limited control over electricity usage	Greater control – users can monitor and manage consumption
Recharging Method	Not applicable	Online recharge via mobile apps, QR codes, and websites
Disconnection for Non-payment	Manual disconnection	Automatic disconnection when balance runs out
Operational Cost	High – due to manual operations	Lower – automated processes reduce manpower needs
Consumer Awareness	Low – no real-time usage tracking	High – real-time data helps in planning and reducing wastage
Tamper Detection	Limited tamper-proofing	Advanced tamper alerts and logs
Data Storage	No data logging or past usage tracking	Stores historical data for usage patterns and billing
Government Monitoring	Minimal	Integrated with utility servers for seamless monitoring
Support for Dynamic Tariffs	No support	Supports time-of-day and dynamic tariff systems
Installation Cost	Lower	Higher initial cost, but long-term savings
Maintenance Requirement	Frequent maintenance needed	Low maintenance due to robust design
Scalability & Future Integration	Limited integration with smart grid systems	Designed for smart grid and future upgrades (e.g., IoT, AI analytics)

In summary, the Smart Prepaid Energy Meter System revolutionizes electricity billing by eliminating traditional postpaid methods and enabling a transparent, efficient, and automated prepaid mechanism. By integrating IoT, QR-based transactions, and real-time monitoring, the system ensures accurate billing, improved energy conservation, and enhanced user convenience. Future enhancements may include AI-powered consumption prediction, mobile app integration, and blockchain-secured transactions to further improve security and scalability.

Comparative Analysis Between Conventional Energy Meters And Prepaid Smart Energy Meters In India

Prepaid smart meters are a modern upgrade over conventional energy meters, offering features like real-time consumption tracking, automated billing, and remote monitoring. Unlike traditional meters that rely on manual readings and postpaid billing, smart meters allow users to recharge in advance and manage their usage more efficiently. They also help reduce human errors, electricity theft, and operational costs. Smart meters support dynamic tariffs and integrate well with future technologies like IoT and smart grids. Though they involve higher initial installation costs, the long-term benefits outweigh the expense. Overall, they enhance transparency, consumer control, and energy efficiency in the power distribution system.

The comparative study clearly highlights the significant advantages of prepaid smart energy meters over conventional meters. Smart meters provide accurate, real-time consumption data, enhance consumer control, and reduce operational burdens on utility providers. The integration of automated billing and remote monitoring has shown to minimize human error and improve billing efficiency. Survey data indicates a noticeable increase in consumer satisfaction, transparency, and awareness when using prepaid systems. Additionally, these meters help in reducing electricity theft through advanced tamper detection mechanisms. Although the initial installation cost is higher, long-term savings and system-wide benefits make prepaid meters a viable and efficient alternative.

RESULTS AND DISCUSSION

The calculate Units function is designed to run periodically, typically once every second, to monitor and manage energy consumption. When it starts, it first updates the current time using the NTP client and stores the epoch time. It then checks whether any protection conditions are active—specifically, over-voltage protection (OVP) or over-load protection (OLP). If either is active, it triggers the corresponding warning, turns off the relay to disconnect the load, and exits the function to prevent further processing.

Assuming everything is normal and no protection is active, the function proceeds to calculate the power being consumed by the connected load. In this example, with a constant 20W load running on a 230V supply, the current drawn is approximately 0.087A.

The power is calculated by multiplying the voltage and current, which gives 20W. This power value is then used to compute the energy consumed in that second. Since energy is calculated in kilowatt-hours (kWh), the function divides the power by 3,600,000 (because 1 kWh = 1000W × 3600 seconds), resulting in approximately 0.00000556 kWh per second.

This small amount of energy is accumulated in two variables: energy Used, which tracks the total energy consumed, and minute Energy, which keeps track of how much energy was used in the last minute. Then, using a predefined unit rate (assumed to be ₹10 per kWh), the code calculates the cost of the consumed energy. However, this cost is only deducted from the balance when it reaches or exceeds ₹1. For a 20W load, it takes 60 seconds to consume about 0.0003336 kWh, which costs only about ₹0.0033. Hence, it would take several minutes for the cost to accumulate enough to deduct from the balance.

While the balance is positive, the relay is kept on, allowing the load to remain powered. The system continuously prints the current energy usage and balance to the serial monitor for user feedback. Additionally, every 60 seconds, it prints the amount of energy consumed in the past minute and resets the counter.

Eventually, as the load keeps consuming power, the cost adds up. For a 20W constant load, it would take about 5 hours to use ₹1 worth of energy, and with an initial balance of ₹5, the system could run continuously for approximately 25 hours.

Once the balance reaches ₹0, the relay is turned off, the power is cut off, and a message saying “Recharge Khatam” is displayed on the serial monitor. The system then waits for a recharge before resuming operation.

International Journal of All Research Education and Scientific Methods (IJARESM),
ISSN: 2455-6211, Volume 13, Issue 5, May-2025, Available online at: www.ijaresm.com

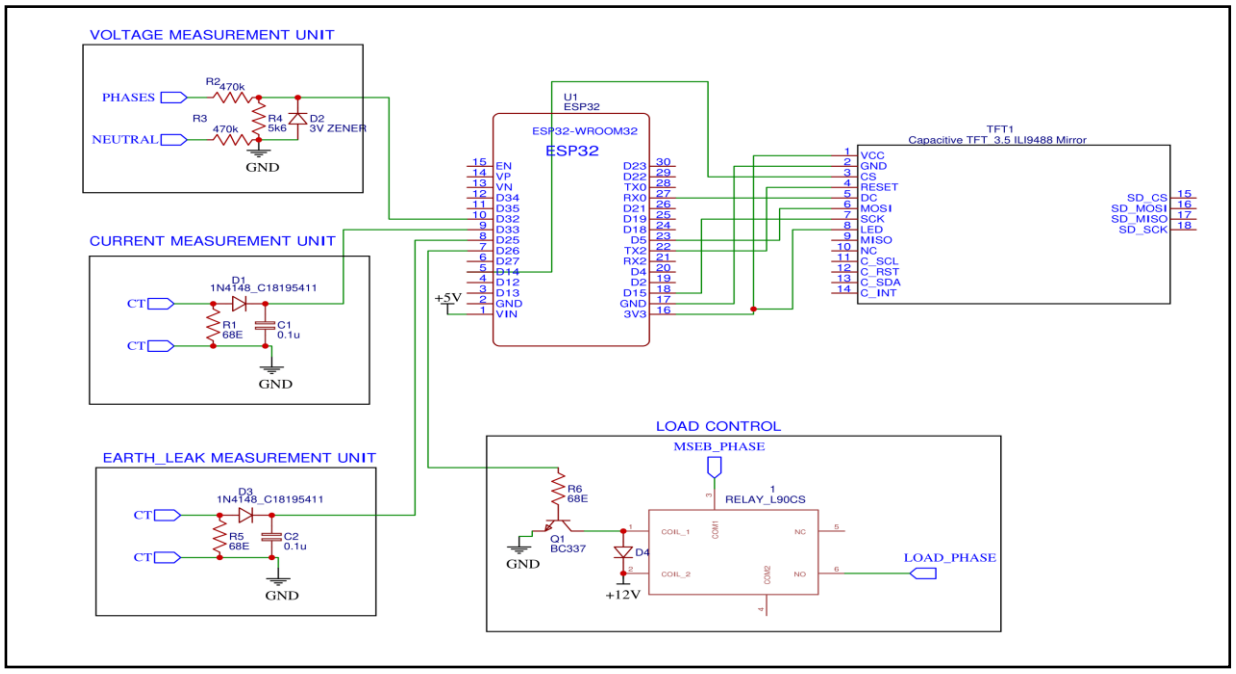

Fig.2 Circuit Diagram Smart Energy Meter System

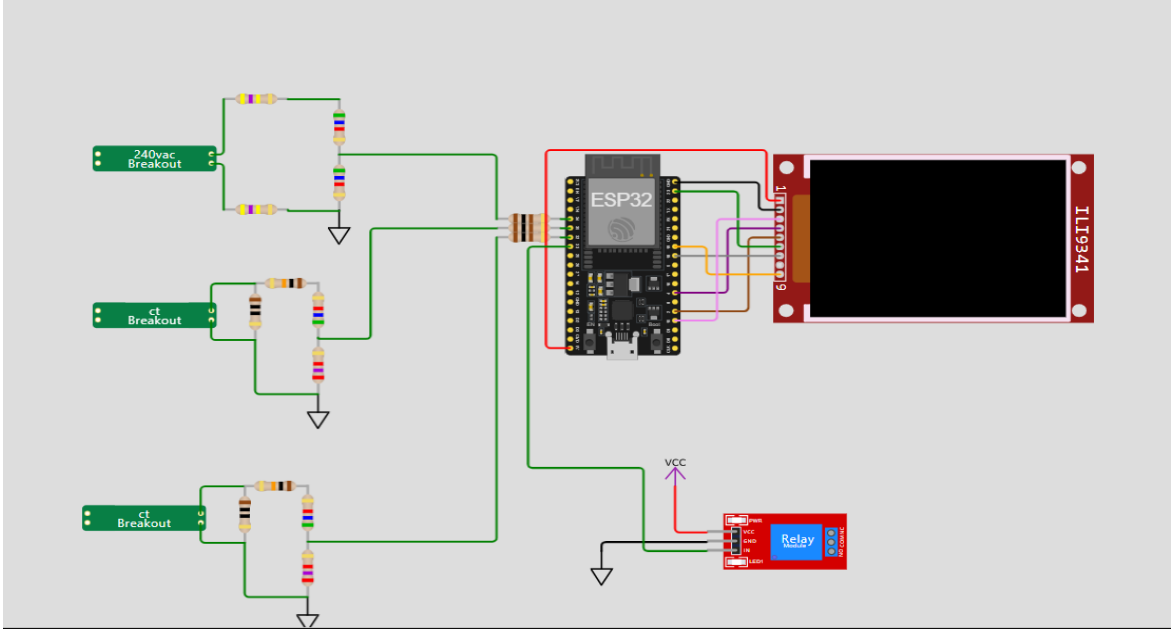

Fig.3 Simulation of Smart Energy Meter System

In Fig 2 provided a schematic representation a comprehensive smart energy monitoring and control system cantered around the ESP32-WROOM32 microcontroller, designed for real-time electrical parameter tracking and load management. The system includes a voltage measurement unit that steps down the AC mains voltage using a resistive divider (470kΩ resistors) and clamps it using a 3V Zener diode to safely feed into the ESP32's ADC for voltage monitoring. The current measurement unit employs a current transformer (CT), with a burden resistor (68Ω), protective diode (1N4148), and filter capacitor (0.1µF) to condition the current signal for analog input to the ESP32, enabling current and power computation. Similarly, the earth leakage measurement unit uses another CT circuit to detect differential current leakage, indicating possible faults, with identical signal conditioning components for safety and noise filtering. The system features a load control circuit that uses a BC337 NPN transistor to drive a 12V relay (L90CS),

allowing the ESP32 to switch the connected load on or off based on monitored parameters. A 3.5-inch ILI9488 capacitive TFT display interfaces via SPI with the ESP32, providing a user-friendly visual output of voltage, current, power, and system status. Powered by a regulated 5V supply, this setup offers integrated sensing, visualization, and control, making it suitable for smart prepaid meters, fault detection, and energy-efficient load management applications in residential and industrial environments.

In Fig 3 the simulation circuit visually demonstrates the working prototype of a smart energy monitoring and control system using an ESP32 microcontroller, aligning with the previously described schematic. A 240V AC breakout is used to simulate mains voltage, which is stepped down through a resistive voltage divider and clamped to a safe level before being fed into the ESP32's analog input for real-time voltage monitoring. Two CT (Current Transformer) breakout modules simulate current and earth leakage measurements, with associated burden resistors and protection diodes conditioning the signal before input to the ESP32's ADC. The microcontroller communicates with a TFT display via SPI interface to present monitored data such as voltage, current, and leakage visually. Additionally, a relay module is interfaced with a digital pin of the ESP32 to simulate load control, switching the load ON or OFF based on sensed electrical conditions. This simulation successfully verifies signal acquisition, data processing, display interaction, and output control, demonstrating the core functionality of a smart energy monitoring system.

Hardware Implementation

Fig 4 Main Interface

The Fig 4 displays the main interface of the device, designed to create awareness and provide at-a-glance information about power usage. The screen shows motivational messages like "Save Energy" and "Save Earth" to encourage responsible electricity use. The real-time consumption is displayed on the right side (1.91 in purple), while the balance in Indian Rupees (₹810) and current voltage (222V) are also prominently shown. The display also includes a timestamp (11:58:56 AM, Thursday, 01 May 2025) and a green button labeled "More" that likely redirects the user to the detailed screen shown in Image 1. The use of vibrant colors and organized layout improves visibility and user interaction. This home screen provides users with immediate, essential information and promotes conscious electricity consumption, fulfilling the smart meter's educational and functional purpose.

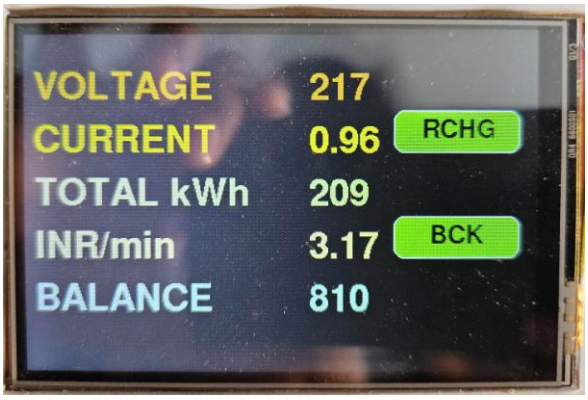

Fig 5 Monitoring Screen

The Fig5 shows the energy meter's detailed monitoring screen on the TFT display, which provides real-time electrical parameters and user account information. The display shows the voltage as 217V and current as 0.96A, indicating that the system is actively monitoring a live electrical load. The total energy consumed is 209 kWh, and the cost of usage is being calculated in INR per minute, displayed as ₹3.17/min. Below this, the remaining balance in the user's account is shown to be ₹810. Two interactive buttons labeled "BCK" and "RCHG" allow the user to navigate back to the main menu or initiate a recharge process, respectively. This interface is critical in helping users understand their real-time power consumption and manage their usage within the prepaid balance, aligning with the project's objective of empowering consumers to control electricity expenses.

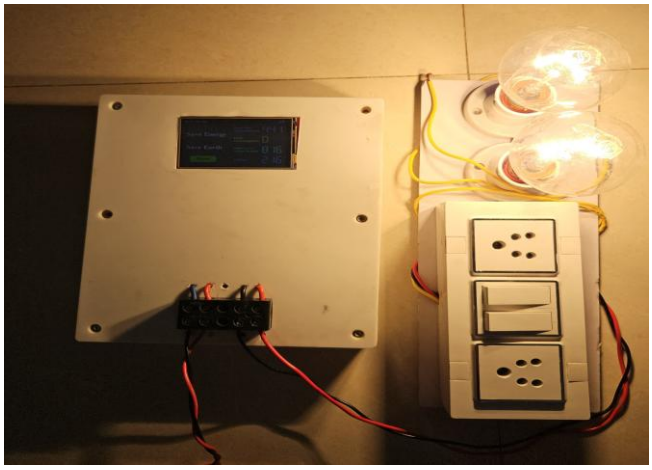

Fig 6 Hardware

The Fig 6 confirms the technical functionality of the smart prepaid energy meter, showing that the ESP32 successfully processes real-time voltage and current data, calculates energy consumption, and controls power delivery through a relay based on the available prepaid balance. The active load (glowing bulbs) demonstrates the effective operation of the sensing, processing, and switching mechanisms, validating the system's real-world performance and its suitability for practical energy management applications.

The successful implementation of the smart prepaid energy meter system has effectively optimized power consumption management, providing real-time monitoring, automatic balance deduction, and safety mechanisms for overvoltage and overload conditions. The system ensures reliability by storing data in EEPROM, allowing for consistent operation even after power cycles. Through its efficient energy usage tracking and cost calculation, it offers a user-friendly, secure, and reliable solution for prepaid energy management, marking a significant achievement in smart metering technology.

CONCLUSION

The smart prepaid energy meter system developed using the ESP32 microcontroller demonstrates a reliable, scalable, and user-centric solution for efficient energy monitoring and load management. Through precise voltage and current sensing circuits, the device accurately measures real-time energy consumption and calculates cost based on predefined tariffs. Its prepaid logic ensures that energy usage is controlled according to user balance, promoting responsible electricity consumption and preventing overuse. The integration of a responsive TFT touchscreen provides a clear and interactive display of essential data such as voltage, current, energy units, cost, and remaining balance, enhancing usability and awareness. The successful simulation and real-time hardware validation confirm that the system's components—including current transformers, voltage dividers, relay switching, and firmware algorithms—function cohesively to deliver consistent performance. Furthermore, the project contributes to energy conservation efforts by empowering users with transparency and control over their consumption. This makes it a practical solution for residential, institutional, or small-scale commercial settings where prepaid energy models are desirable for economic and operational efficiency.

REFERENCES

[1]. M. S. Parvin and S. M. Lutful Kabir, "A framework of a smart system for prepaid electric metering scheme," 2015 International Conference on Informatics, Electronics & Vision (ICIEV), Fukuoka, Japan, 2015, pp. 1-5.
[2]. Franek, Lešek. (2013). Prepaid Energy in Time of Smart Metering. IFAC Proceedings Volumes. 46. 428-433. 10.3182/20130925-3-CZ-3023.00015.
[3]. M. W. Raad, T. Sheltami and M. Sallout, "A Smart Card Based Prepaid Electricity System," 2007 2nd International Conference on Pervasive Computing and Applications, Birmingham, UK, 2007, pp. 219-224.

[4]. Sahani B, Ravi T, Tamboli A, Pisal R. IoT based smart energy meter. International Research Journal of Engineering and Technology (IRJET). 2017 Apr;4(04):96-102.
[5]. Ask, Kumar, Navneet Kumar Singh, Asheesh Kumar Singh, Dinesh Kumar Singh, and Kundan Anand. "Design and simulation of smart prepaid-postpaid energy meter with alarm and theft control." In 2018 5th IEEE Uttar Pradesh Section International Conference on Electrical, Electronics and Computer Engineering (UPCON), pp. 1-6. IEEE, 2018.
[6]. Mohammad, Nabil, Anomadarshi Barua, and Muhammad Abdullah Arafat. "A smart prepaid energy metering system to control electricity theft." In 2013 international conference on power, energy and control (ICPEC), pp. 562-565. IEEE, 2013.
[7]. Reddy, P. Rahul, Rajashekhar Kammanaboina, Dumpa Prasad, Prabhakara Rao Kapula, and Asisa Kumar Panigrahy. "Implementation of smart energy meter through prepaid transaction using IoT." In 2021 International Conference on Recent Trends on Electronics, Information, Communication & Technology (RTEICT), pp. 310-314. IEEE, 2021.
[8]. Rathee, Sagar, Aayush Goyal, and Anup Shukla. "Designing prepaid smart energy meter and deployment in a network." In 2020 IEEE 4th Information Technology, Networking, Electronic and Automation Control Conference (ITNEC), vol. 1, pp. 1208-1211. IEEE, 2020.
[9]. Kaliappan, E., D. Fathema Farzana, B. Ponkarthika, G. Vignesh, T. Kesavan, and T. Abhishek Dheeven. "IOT Based Smart Prepaid Energy Recharge Scheme for EB." In 2022 International Conference on Computer Communication and Informatics (ICCCI), pp. 1-6. IEEE, 2022.
[10]. Preethi, V. and Harish, G., 2016, August. Design and implementation of smart energy meter. In 2016 International Conference on Inventive Computation Technologies (ICICT) (Vol. 1, pp. 1-5). IEEE.
[11]. Yaghmaee, M.H. and Hejazi, H., 2018, August. Design and implementation of an Internet of Things based smart energy metering. In 2018 IEEE International Conference on Smart Energy Grid Engineering (SEGE) (pp. 191-194). IEEE.
[12]. Saha, Saikat, Swagata Mondal, Anindya Saha, and P. Purkait. "Design and implementation of IoT based smart energy meter." In 2018 IEEE Applied Signal Processing Conference (ASPCON), pp. 19-23. IEEE, 2018.